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Abstract

A static (wind-off) test was conducted in the static test facility of the Langley 16-Foot Transonic Tunnel to evaluate the vectoring capability and isolated nozzle performance of the proposed thrust vectoring system of the F/A-18 high-alpha research vehicle (HARV). The thrust vectoring system consisted of three asymmetrically spaced vanes installed externally on a single test nozzle. Two nozzle configurations were tested: a maximum afterburner-power nozzle and a military-power nozzle. Vane size and vane actuation geometry were investigated, and an extensive matrix of vane deflection angles was tested. The nozzle pressure ratio ranged from 2 to 6. The results indicate that the three-vane system can successfully generate multiaxis (pitch and yaw) thrust vectoring. However, large resultant vector angles incurred large thrust losses. Resultant vector angles were always lower than the vane deflection angles. The maximum thrust vectoring angles achieved for the military-power nozzle were larger than the angles achieved for the maximum afterburner-power nozzle.

Introduction

The next generation of fighter/attack aircraft must surpass current configurations in high-speed and low-speed agility, maneuverability, and high-angle-of-attack (high-alpha) capability to ensure survivability and air superiority. Over the last decade, numerous studies have been conducted to determine how the best qualities of today's fighter aircraft can be enhanced and extended. One potential enhancement of aircraft control power is the addition of a multiaxis thrust vectoring system to the aircraft propulsion geometry and controls package (refs. 1–10). A multiaxis thrust vectoring system would deflect the exhaust jet or jets to provide longitudinal and directional control power in flight regimes where conventional aerodynamic controls may fail. Thrust vectoring can extend maneuvering capability to both low-speed and high-speed flight conditions and increase the angle-of-attack range to the extremes of post-stall maneuvering or "supermaneuverability."

The F/A-18 high-alpha research vehicle (HARV) is a prototype F/A-18 aircraft being modified specifically for flight research at high angles of attack up to 70° (refs. 10–13). The baseline F/A-18 aircraft is a highly maneuverable twin-engine fighter aircraft with some high-alpha capability. One of the HARV adaptations to the baseline aircraft is the modification of the conventional axisymmetric-nozzle propulsion system into a multiaxis thrust vectoring system. Studies of axisymmetric thrust-vectoring concepts indicate that these systems can indeed provide effective levels of multiaxis flow turning (refs. 14–19). Thrust vectoring concepts for axisymmetric nozzles that have been researched include gimballed nozzles (refs. 15 and 19), swiveling or hinged nozzles (refs. 15 and 18), and externally mounted deflecting vanes (refs. 16 and 17). The external-vane multiaxis vectoring concept was chosen for the F/A-18 HARV because the thrust vectoring vane system required no nozzle development and could be easily adapted to the F/A-18 afterbody with little interference on existing control surfaces. To add the vanes with minimal afterbody changes, the divergent section of the nozzle was removed. The vane system consisted of three asymmetrically spaced vanes installed on each nozzle. The vanes were designed to fully retract away from the exhaust flow during unvectored operation. It was assumed that only two vanes would deflect into the jet at any given time. An artist's concept of the F/A-18 HARV with the proposed multiaxis vectoring system installed is shown in figure 1.

To initially evaluate the vectoring capability and isolated nozzle performance of the F/A-18 HARV thrust vectoring system, a static (wind-off) test was conducted in the static test facility of the Langley 16-Foot Transonic Tunnel. High-pressure air was used to simulate the jet flow. Nozzle pressure ratio was varied from 2 to 6. The operational nozzle pressure ratio for the F/A-18 HARV is approximately 4 at a Mach number of 0.3. The test hardware simulated the nozzle–vane geometry for one engine only, the left engine. The models were sized to 14.25 percent of full scale. Two nozzle configurations were tested: a maximum afterburner-power nozzle (with a large throat area) and a military-power nozzle (with a small throat area). Vane size and two different vane-actuation geometries were also investigated. The number of vanes deployed and the vane angles were varied to produce a thrust vectoring envelope for each nozzle configuration. Results are presented as nozzle internal performance and resultant thrust vector angles. Selected results of this experiment were presented in an earlier report (ref. 20).

Symbols

All forces (except for resultant gross thrust) and angles are referred to the model centerline.

A_t	nozzle throat area (the minimum internal geometric area), in^2
D	maximum external nozzle diameter, in.
d_t	nozzle throat (minimum) diameter, in.
F	measured thrust along body axis, positive in forward direction, lbf
F_i	ideal isentropic gross thrust, lbf, $w_p \left\{ \frac{R_j T_{t,j}}{g^2} \frac{2\gamma}{\gamma - 1} \left[1 - \left(\frac{1}{\text{NPR}} \right)^{(\gamma-1)/\gamma} \right] \right\}^{1/2}$
F_N	measured normal force, lbf
F_r	resultant gross thrust, lbf, $\sqrt{F^2 + F_N^2 + F_S^2}$
F_S	measured side force, lbf
g	acceleration due to gravity (where $1g \approx 32.174$ ft/sec^2)
H	height from nozzle centerline to bottom of vane mounting bracket, in.
L	total length of nozzle from attachment station to exit, in.
p_a	ambient pressure, psi
$p_{t,j}$	average jet total pressure, psi
R	height of shims used to position vane actuation hardware (see fig. 6), in.
R_j	gas constant, 1716 ft^2/sec^2-°R
r	vertical coordinate, measured from nozzle internal centerline, used to define vane center of rotation (see fig. 6), in.
$T_{t,j}$	jet total temperature, °R
w_i	ideal weight-flow rate, lbf/sec
w_p	measured weight-flow rate, lbf/sec
X	length measured from downstream face of nozzle attachment flange to start of vane actuation system (see fig. 6), in.
x	axial coordinate, measured from nozzle attachment station, used to define vane center of rotation (see fig. 6), in.
α	nozzle internal convergence angle, deg
γ	ratio of specific heats, 1.3997 for air
δ_{A}, δ_{B}, δ_{C}	geometric deflection angle of vanes at positions A, B, and C, respectively, deg
δ_p	resultant pitch thrust vector angle, $\tan^{-1} \frac{F_N}{F}$, deg
δ_y	resultant yaw thrust vector angle, $\tan^{-1} \frac{F_S}{F}$, deg

Abbreviations:

A	vane position A
A/B	afterburner
B	vane position B
C	vane position C
HARV	high-alpha research vehicle
max	maximum
mil	military
NPR	nozzle pressure ratio, $p_{t,j}/p_a$
Sta.	model station, in.

Apparatus and Methods

Static Test Facility

This test was conducted in the static test facility of the Langley 16-Foot Transonic Tunnel. A detailed description of this facility is given in reference 21. The test facility completely houses a single-engine cold-air propulsion simulation system and a control room. Testing is conducted by exhausting a high-pressure air jet to atmosphere in a large, vented and acoustically treated room inside the facility. The control room is separated from the test area and is sealed from any jet-induced noise. During testing, all operation of the propulsion simulation system is conducted from the control room, and a closed-circuit television is used to observe the model.

The high-pressure air system of the static test facility uses the same clean, dry air supply available to the 16-Foot Tunnel. The air control system includes valving and filters to ensure air quality and accurate repeatablity of pressure levels. A heat exchanger maintains the compressed air jet at constant stagnation temperature. This air system is very similar to the high-pressure air system of the 16-Foot Tunnel (ref. 21).

Single-Engine Propulsion Simulation System

A sketch of the single-engine propulsion simulation system with a nozzle–single-vane test configuration installed is presented in figure 2. The propulsion simulator is shown with the military-power nozzle and a single vectoring vane installed in the top mounting bracket. A photograph of the single-engine system with a nozzle–three-vane configuration is presented in figure 3.

An external high-pressure air system provided a continuous flow of clean, dry air maintained at a temperature of approximately 540°R. This high-pressure air was varied during jet simulation up to about 90 psia in the nozzle. The pressurized air was transferred from the supply source to the simulator by six air lines that run through a dolly-mounted support strut and into a high-pressure plenum chamber. The air was then discharged perpendicularly into the model low-pressure plenum through eight multiholed sonic nozzles that were equally spaced around the high-pressure plenum. The high-pressure plenum was separated from the balance system, but the low-pressure plenum was attached to the balance. This particular airflow system was designed to minimize any forces generated by the transfer of axial momentum as the air passed from the nonmetric high-pressure plenum to the metric low-pressure plenum. Two flexible metal bellows sealed the air system between the metric and nonmetric plenums and compensated for forces resulting from pressurization.

From the low-pressure plenum, the air passed through a circular choke plate into an instrumentation section, and then into the exhaust nozzle. The same instrumentation section and choke plate were used for all nozzle configurations tested. The test nozzles were mounted to the instrumentation section at model station 39.235.

Nozzle Geometry

The nozzle design used in this experiment was a 14.25-percent-scale model of the F/A-18 axisymmetric convergent-divergent nozzle with the divergent section of the nozzle removed, thus resulting in a purely convergent nozzle. Eliminating the divergent section allowed easier installation of the vane actuation system and minimized the weight increase that resulted from adding the thrust vectoring vanes to the F/A-18 aircraft. Two nozzle configurations were tested. One configuration represented a maximum afterburner-power (A/B) setting (large throat area), and the other represented a military-power setting (small throat area). Details of the nozzle geometry are presented in figure 4.

Vane Geometry

The three-vane thrust vectoring geometry reported in reference 16 provided the basis for the vane actuation geometry and vane design for the F/A-18 HARV static test hardware. The vane design for the F/A-18 thrust vectoring system consisted of three equally sized vanes placed asymmetrically about the nozzle exit. The vanes were designed for maximum thrust vector angles when installed on the maximum A/B-power nozzle. A larger vane was later proposed for installation in the top vane position (position A). As a result, two different vane sizes were tested, and one of the test objectives was the determination of vane size for the top vane. Sketches of the two vane geometries are presented in figure 5. The original vane is referred to as the *standard* vane, and the oversized vane is referred to as the *large* vane.

Each vane was designed with double curvature, i.e., axial and radial curvature, on the vectoring surface. The vane planform area was 5.337 in^2 for the standard vane and 7.304 in^2 for the large vane. Thus, the large vane was approximately 27 percent greater in planform area than the standard vane. The vanes had clipped corners at the trailing edge. This corner geometry allowed complete closure of any two vanes to angles of 35° without physical interference between the vanes. During thrust vectoring, only one or two vanes were deflected into the jet while the third vane remained retracted (out of the jet flow).

Vane Actuation System

Sketches of the geometries of the simulated vane actuation system are presented in figure 6. The thrust vectoring vanes were initially attached to a mounting plate. The plate was then fastened by two bolts to a mounting bar through a curved, machined slot in the plate, as shown in figure 6. The arrangement of the curved slot and bolt allowed vane deflection from −15° (out of the jet) to 35° (into the jet). When the vane deflection angle was set, an angle block was used to verify the actual inclination of the vane and to ensure repeatability of each vane position. A separate angle block was required for each deflection angle tested.

The vane-mounting hardware was designed to simulate two different vane actuation systems: a translating vane system and a rotating vane system.

One of the test objectives was the evaluation of these two systems. The translating vane system was designed to rotate the vane to set the deflection angle, and then to translate the vane axially and radially into the jet stream. The rotating vane system was designed to simply rotate the vane into the jet flow to set the deflection angle. To simulate the positions of the vane as set by each of the full-scale actuation systems, the position of the mounting bar was adjusted to set each deflection angle.

Figure 6(a) shows the coordinates X and R that defined the position of the mounting bar and vane for each actuation system and each vane deflection angle. The mounting bar was adjusted radially (varying R) by adding or removing thin metal shims. The bar was adjusted axially (varying X) by positioning the bar through a slot in the mounting hardware. The relationship between the vane center of rotation (the coordinates x and r) and the radial and axial position (the coordinates X and R) is defined by the two equations given in figure 6(b). The vane center of rotation was always fixed with respect to the nozzle centerline. Note that several sets of X and R are presented for a vane deflection angle of 25° in the translating vane system. This set of coordinates defines specific points along the path of translation of the vane into the jet after the vane has been rotated to 25°. For the rotating vane system, only one set of X and R values was required to define the position of the deployed vane.

Figure 7 presents sketches detailing the vane positions relative to the nozzle exit for both test nozzles. Photographs of the vanes installed on the military-power nozzle are presented in figure 8. The three thrust vectoring vanes were arranged circumferentially about the nozzle exit and spaced asymmetrically to interface with existing structural hardpoints on the F/A-18 aircraft. The "top" vane (vane A) was located 5° counterclockwise from the vertical centerline of the nozzle. This position did not vary with vane size. The "outboard" vane (vane B) was located 118° counterclockwise from the mounting point of vane A. The "inboard" vane (vane C) was located 138.5° clockwise from the mounting point of vane A. The vane positions were identical for both test nozzles. Note that the vanes were physically closer to the jet plume when actuated on the maximum A/B-power nozzle.

Instrumentation

A six-component strain-gauge balance was used to measure forces and moments on the metric portion of the model. Total pressure in the jet was measured by a nine-probe rake fixed in the instrumentation section. The total pressure rake is shown in figure 2. The nozzle total pressure was computed as the average of the individual total pressures. In addition, a thermocouple was positioned in the rake plane to measure jet total temperature. The measured weight-flow rate of the high-pressure air supplied to the nozzle was calculated from temperature and pressure measurements taken in two calibrated, choked venturi systems located in the external air system. (See ref. 21.)

Data Reduction

Fifty frames of data, acquired at the rate of 10 frames per second over a 5-sec sample interval, were averaged for each measured data parameter at each data point. The averaged values were used in all subsequent computations. Each of the six measured balance components was initially corrected for model weight tares, for balance component interactions, and for jet-off balance interactions that result from the balance installation.

An additional correction was required to remove model pressurization effects (bellows tares). Although the bellows arrangement in the high-pressure air system was designed to eliminate pressure and momentum interactions with the balance, small bellows tares on the six balance components are generated by jet operation. These tares result from a small pressure difference between the ends of the bellows when air-system internal velocities are high and from small differences in the spring constants of the upstream and downstream bellows when the bellows are pressurized. The bellows tares were determined by testing Stratford choke calibration nozzles (ref. 22) with documented performance over the range of expected internal pressures and external forces and moments. Details of the Stratford nozzles used to calibrate the balance–air system are presented in reference 22. The resulting tare factors were then applied to complete the corrections of the six balance components. The procedure for correcting balance measurements is documented in reference 23.

Five computed performance parameters are used to evaluate the results of this experiment: internal thrust ratio F/F_i, resultant thrust ratio F_r/F_i, discharge coefficient w_p/w_i, resultant pitch vector angle δ_p, and resultant yaw vector angle δ_y. All balance data (i.e., thrust parameters and vector angles) except the resultant gross thrust F_r were referenced to the model centerline.

Internal thrust ratio F/F_i is the ratio of the measured nozzle thrust along the body axis to the ideal isentropic gross thrust of the nozzle. The nozzle internal thrust F is equivalent to the fully corrected axial force measured by the balance. The ideal thrust F_i is computed from the measured weight-flow rate w_p, the average jet total pressure $p_{t,j}$, and the jet total temperature $T_{t,j}$. (See the exact definitions in the *Symbols* section.) The thrust along the body axis F is diminished by any deflection of the exhaust vector away from the axial direction.

The resultant thrust ratio F_r/F_i is the ratio of the nozzle resultant gross thrust F_r to the ideal thrust F_i. Resultant thrust is computed from the fully corrected balance measurements of axial-force, normal-force, and side-force components of the jet resultant force. This thrust parameter is not diminished by actual jet-flow deflection but is indicative of other losses, inherent in the nozzle–vane system, caused by turning the exhaust flow.

The nozzle discharge coefficient w_p/w_i is the ratio of measured weight-flow rate to ideal weight-flow rate. This parameter reflects the ability of a nozzle to pass weight flow. A decrease in discharge coefficient for a given nozzle design reflects momentum and vena contracta losses.

The resultant thrust vector angles reflect the degree of actual jet-flow deflection away from the axial direction. The resultant pitch vector angle δ_p is computed from axial-force and normal-force measurements; the resultant yaw vector angle δ_y is computed from axial-force and side-force measurements.

Results and Discussion

The results of this investigation are presented in both tabular and plotted form. Performance data for each configuration tested are presented in tables. All five computed performance parameters (F/F_i, F_r/F_i, w_p/w_i, δ_p, and δ_y) are tabulated for each jet-on data point; the nozzle pressure ratio (NPR) is also presented. Table 1 provides an index to the tabulated data presented in tables 2–90. Performance parameters for the maximum A/B-power nozzle without vanes are presented in table 2. The performance of the maximum A/B-power nozzle with vane(s) installed is presented in tables 3–68. Performance parameters for the military-power nozzle without vanes are presented in table 69. The performance of the military-power nozzle with vane(s) installed is presented in tables 70–90. Only results for selected configurations will be presented as data plots. Comparison and summary plots for selected configurations are presented in figures 9–19.

Baseline Nozzle Performance

The isolated nozzle performance of the two test nozzles without vectoring vanes installed is presented in figure 9. Axial thrust ratio F/F_i, resultant thrust ratio F_r/F_i, and discharge coefficient w_p/w_i are presented as functions of nozzle pressure ratio NPR. The baseline nozzles without vanes were run at intervals throughout the test to verify the repeatability of the data. All repeat data runs are plotted in the figure. For the baseline nozzles, gross thrust ratio and axial thrust ratios are essentially identical since no vectoring is implemented. The thrust data show typical trends of convergent nozzle performance. Thrust ratios reach a peak when choke flow conditions are established at the nozzle throat (NPR = 1.89), and then they degrade as NPR increases. Thrust losses are caused by flow underexpansion effects.

Discharge coefficient levels differ between the two nozzles because discharge coefficient w_p/w_i is influenced by the nozzle internal geometry upstream of and in the vicinity of the nozzle throat. The maximum A/B-power nozzle achieves a higher level of w_p/w_i than the military-power nozzle because it has a lower internal convergence angle α. (See fig. 4.) The lower convergence angle results in smaller vena contracta losses and, thus, in higher values of discharge coefficient. For both nozzles, w_p/w_i is relatively constant with NPR once the nozzle flow has choked. Such trends are typical for convergent nozzles (ref. 22). Geometric changes downstream of the nozzle throat plane do not generally affect the discharge coefficient. For the F/A-18 nozzles of this investigation, thrust vectoring by vane deflection is always implemented downstream of the nozzle throat and results in insignificant effects on w_p/w_i. Consequently, w_p/w_i is not plotted for the vectoring configurations since trends essentially mirror the baseline nozzle results. However, discharge coefficient data are presented in the tables for each test configuration.

Before continuing with the discussion of the F/A-18 nozzle data, some general performance characteristics of externally mounted thrust vectoring vanes should be noted. Positive deflection of externally mounted vanes produces flow turning but diminishes axial and resultant thrust ratios. The axial thrust is decreased with thrust vectoring because vane deflection diverts flow away from the axial direction. The resultant thrust ratio, however, includes lateral and longitudinal components and is not affected by diverting axial thrust into another plane. Resultant thrust losses occur because the externally mounted vanes deploy into supersonic jet flow. Increased thrust losses were probably caused by additional aerodynamic turning losses (such as shock, friction, and/or pressure losses). Thrust losses with the external vane thrust vectoring concept were observed in an earlier study (see ref. 16) and were an expected result of the F/A-18 vane investigation. These losses increase with increasing positive deflection angles and with the number of vanes deployed (set at positive deflection angles). Negative vane deflections produce little or no flow turning and, consequently, have essentially no effect on axial or resultant thrust ratio.

Effect of Vane Actuation Geometry

The effects of the two different vane actuation systems on nozzle performance are presented in figure 10. Thrust ratios, resultant pitch vector angle δ_p, and resultant yaw vector angle δ_y are presented as functions of NPR. The open symbols represent the translating vane data and the solid symbols represent the rotating vane data. Results are shown for the three standard-size vanes installed on the maximum A/B-power nozzle. For a given configuration, either one or two of the vanes were deflected into the jet (deployed) while the third vane was installed but positioned away from the jet (retracted). In this report, a geometric vane angle of -10° will always be considered the fully retracted vane position, and a positive vane angle ($>0^\circ$) will be considered a deployed vane setting.

The magnitudes and direction of the resultant thrust vector angles depend on which vane or vanes are deployed and on how many vanes are deployed. Of the data sets for the six vane geometries presented in figure 10, all but one showed larger magnitudes of both δ_p and δ_y for the rotating vane actuation system, especially at low values of NPR. In figure 10(c), the configuration with $\delta_{\rm A} = 25^\circ$, $\delta_{\rm B} = -10^\circ$, and $\delta_{\rm C} = 25^\circ$ results in slightly lower pitch and yaw angles for the rotating vane system at values of NPR > 4. When resultant vector angles were larger, thrust losses were also larger for the rotating vane system. However, the primary objective of the vane actuation study was to determine which actuation geometry generated the largest possible vectoring envelope, not the smallest thrust losses. As mentioned previously, thrust losses were expected for the large vane deflections.

From a full-scale geometry viewpoint, the rotating vane system would probably be the preferred actuation system. The rotating vane actuating mechanism would be simpler (one movement: a rotation) than the translating vane actuating mechanism (two movements: a translation and a rotation). As a result, the full-scale rotating vane hardware would be lighter in total weight. In addition, vane actuation rates would probably be greater for the simpler rotating mechanism. Based on the full-scale application and the generally larger thrust vectoring angles, the rotating vane actuation system was chosen over the translating vane actuation system for the remaining test configurations.

Effect of Top Vane Geometry

The objective of testing two different vane geometries at the top vane position (position A) was to determine which three-vane geometry would produce the largest equal amount of positive and negative pitch vector angles (nose-up and nose-down moments on the aircraft). A balanced pitch vectoring envelope is essential in establishing aircraft stability and post-stall recovery capability. The position of the two lower vanes sets the magnitude of negative pitch vectoring. The size of the top vane was increased in an attempt to raise the maximum levels of positive pitch vectoring. Results are presented in figure 11 for the vanes installed on the maximum A/B-power nozzle and in figure 12 for the vanes installed on the military-power nozzle. The open symbols denote data resulting from testing three standard vanes, and the solid symbols denote data resulting from testing the standard vanes at positions B (outboard) and C (inboard) and the large vane at position A.

For specific cases (illustrated in fig. 11) when vane A was not deployed, the three standard vanes produced a larger magnitude of negative pitch vectoring than the combination of the large and standard vanes (referred to herein as the *large–standard combination*). Increased impingement of the vectored jet flow on the retracted large top vane probably restricted the magnitude of the resultant pitch vector angles. Overall, however, the installation of the large vane produced more equally balanced magnitudes of positive and negative resultant pitch vector angles than the use of three standard vanes. For example, at NPR = 3, the large–standard vane combination installed on the maximum A/B-power nozzle resulted in pitch vector angles from -23° to 19°, whereas the standard vane combinations resulted in pitch vector angles from -26° to 8°. Thus, the large–standard vane combination produced a pitch-thrust vectoring envelope that was less biased toward the negative direction.

The military-power nozzle with vanes installed produced larger resultant vector angles than the maximum A/B-power nozzle with vanes. The military-power nozzle generated a smaller jet diameter such that the deployed vane or vanes affected a larger percentage of the jet plume, and thus it produced proportionally larger amounts of flow turning.

However, the vanes produced the same effects on resultant vector angle regardless of nozzle power-setting geometry. Again, the large–standard vane combination produced a larger positive range of pitch vector angles than the standard vanes and generated a thrust vector envelope that was less biased toward negative pitch vector angles. At NPR = 3, the large–standard vane combination installed on the military-power nozzle produced pitch vector angles from $-32°$ to $22°$, whereas the standard vane combinations produced pitch vector angles from $-36°$ to $12°$. Selected geometries of the standard vane combinations without vane A deployed resulted in slightly higher negative pitch vector angles than the large–standard combination. (See fig. 12.)

In summary, the large–standard vane combination generated a more balanced positive and negative pitch vectoring envelope for both nozzle power setting geometries. This vane geometry and arrangement were eventually selected for the F/A-18 HARV flight hardware. The remaining data figures will present results from the large–standard vane combinations, not the three standard vanes.

Effects of Parametric Vane Deflections

The remaining configurations were tested to provide a thrust vectoring envelope for each test nozzle. A very detailed matrix of vane deflections was tested for the maximum A/B-power nozzle to completely establish the thrust vectoring capabilities of the nozzle–vane system. A coarser vane deflection matrix was tested for the military-power nozzle. The military-power thrust vectoring envelope should equal or surpass the maximum A/B-power envelope because the vanes, which were sized for the maximum A/B-power nozzle, would affect a larger percentage of the jet plume for the military-power nozzle.

To determine the thrust vectoring envelope, at least one vane was always fully retracted with one or two vanes deployed into the jet flow. Three vanes were always installed for the envelope configurations. The matrix of the maximum A/B vane deflection was subdivided as follows: a single vane deployed, two vanes equally deployed, and two vanes deployed with unequal angles. The maximum A/B nozzle results for the parametric vane deflections are presented in figures 13–15. Results for a single vane deployed and two vanes retracted are presented in figure 13. Results for two equally deployed vanes with one vane retracted are presented in figure 14, and results for two unequally deployed vanes with one vane retracted are presented in figure 15. Data are presented as thrust ratios F/F_i and F_r/F_i and resultant thrust vector angles δ_p and δ_y.

Certain trends dominated the vectored-thrust data. Resultant thrust vector angles were always less than the geometric deflection angle of the vane or vanes. In addition, large amounts of flow turning were always accompanied by large thrust losses because the external vanes deflected into supersonic flow. As stated previously, these trends were expected from the results of an earlier study (ref. 16). Flow turning increased with increasing positive vane deflection, as did thrust losses. Because the vanes were arranged asymmetrically about the nozzle exit, pitch vectoring was always coupled with yaw vectoring. However, certain combinations of vane deflections produced pure pitch or pure yaw resultant vector angles. The dominant vectoring direction depended on which vane or vanes were deployed.

The resultant vector angles for the maximum A/B-power nozzle did not always remain constant with NPR, a result which could complicate the in-flight use of this type of vectored-thrust control-power system. Thrust vector angles increased or decreased with increasing NPR depending on which vane or vanes were deployed and on the magnitude of the deployment angle. Generally, vanes deployed to lower angles ($<20°$) produced resultant vector angles that were constant or increased with increasing NPR, whereas vanes deployed to higher angles ($\geq 20°$) produced thrust vector angles that decreased with increasing NPR. For example, single and multiple deployments involving vane A produced pitch vector angles that increased with NPR for vane deployments from $0°$ to $15°$. When vane angles were set to $20°$ or higher, pitch vector angle decreased with increasing NPR. The increase of thrust vector angle with increasing NPR for low vane deployment angles probably reflects a favorable interaction of the deflected vane with the jet plume boundary as the plume expands. The drop in resultant vector angles at higher values of NPR may result from increasing impingement effects of the retracted vane or vanes on the vectored jet plume.

The military-power-nozzle results for the parametric vane deflections are presented in figures 16 and 17. Results for a single vane deployed and two vanes retracted are presented in figure 16. Results for two equally deployed vanes with one vane retracted are presented in figure 17. Data are presented as thrust ratios F/F_i and F_r/F_i and resultant thrust vector angles δ_p and δ_y.

The same trends in performance and thrust vectoring observed for the maximum A/B-power nozzle were also apparent in the military-power-nozzle data. However, for the same vane deployments, resultant thrust vector angles were larger for the military-power nozzle than for the maximum A/B-power nozzle. As discussed earlier, the vane or vanes deployed on the military-power nozzle affected a larger percentage of the jet plume and thus produced proportionally larger amounts of flow turning. For example, when vane A was deployed to 35° with vanes B and C fully retracted, the maximum pitch vector angle generated was 23°, compared with 21° for the maximum A/B-power nozzle.

One trend that differed between the two nozzle–vane configurations was the effect of increasing NPR on resultant vector angles. For the maximum A/B-power nozzle, the effect of NPR varied with vane deployment angle. For the military-power nozzle, the trend is a predominantly favorable effect; flow turning remains constant or increases with increasing NPR. The increase in vector angle begins to drop off only at the maximum vane deflection angle for the maximum NPR value. The negative impingement effects of the retracted vane or vanes seen for the maximum A/B-power nozzle are apparently reduced for the military-power configurations because the retracted vane or vanes affect a proportionally smaller area of jet flow for the smaller military-power jet plume.

Thrust Vectoring Envelopes

The results of the parametric vane deployments are summarized as thrust vectoring envelopes. Results are presented as δ_p plotted against δ_y up to a maximum vane deployment angle of 30°. The vectoring envelope for the maximum A/B nozzle is presented in figure 18. The military-power envelope is plotted along with the maximum A/B-power envelope in figure 19 so that the magnitudes of thrust vectoring capability can be directly compared. Recall that the operational NPR of the F/A-18 HARV at a free-stream Mach number of 0.3 is approximately 4 for both maximum A/B-power and military-power nozzles.

A separate envelope is presented for each NPR tested. These envelopes illustrated that the net flow turning is always less than the vane deflection angles, as was mentioned previously. The envelopes are also asymmetric, a result of the use of three thrust vectoring vanes positioned asymmetrically around the circumference of the nozzle exit. However, pure pitch or pure yaw vector angles were generated by certain vane deflection combinations, a result indicating that isolated moments could be successfully produced by a three-vane vectoring system. Pitch vectoring capability exceeds the yaw vectoring capability, but this was an anticipated result of the vane geometry. The degrading magnitude of peak resultant vector angle with increasing NPR can be seen by comparing the envelope boundaries for different values of NPR. Finally, the comparison of the maximum A/B-power envelope with the military-power envelope in figure 19 illustrates the increased turning effectiveness of the vanes when actuated on the military-power nozzle.

Conclusions

A static (wind-off) test was conducted in the static test facility of the Langley 16-Foot Transonic Tunnel to evaluate the vectoring capability and isolated nozzle performance of the proposed thrust vectoring system of the F/A-18 high-alpha research vehicle (HARV). The thrust vectoring system consisted of three asymmetrically spaced vanes installed externally on the test nozzle. Two nozzle configurations were tested: a maximum afterburner-power nozzle and a military-power nozzle. Vane size and vane actuation geometry were also investigated. The results of this experiment are summarized as follows:

1. A simple rotating vane actuation system generally produced larger resultant thrust vector angles than a translating–rotating vane concept. The rotating vane system was chosen for the F/A-18 HARV thrust vectoring system.

2. The vane geometry chosen for the three thrust vectoring vanes consisted of a large vane mounted on top of the nozzle and two smaller vanes installed at inboard and outboard positions. This vane arrangement produced more balanced amounts of positive and negative resultant pitch vector angles than an arrangement of three equally sized vanes.

3. Because the externally mounted vanes deployed into supersonic jet flow, effective thrust vectoring always resulted in axial and resultant thrust losses. Thrust losses increased with increased vectoring. Thrust vector angles were always less than the geometric vane deployment angles.

4. Because vectoring was implemented with three vanes arranged asymmetrically about the nozzle exit, pitch and yaw vectoring were always coupled. However, certain combinations of vane deflections successfully produced pure pitch vector angles or pure yaw vector angles.

5. For both nozzles tested, the resultant vector angles showed some variation with nozzle pressure ratio.

6. The thrust vectoring envelope was larger for the military-power nozzle than for the maximum afterburner-power nozzle.

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Table 1. Index to Data Tables

(a) Maximum afterburner-power nozzle

Table 1. Concluded

Table 2. Maximum A/B-Power Nozzle Performance
With No Vanes Installed

[δ_p and δ_y are given in degrees]

(a) Run 39

(b) Run 241

Table 3. Maximum A/B-Power Nozzle Performance of
Translating Vane Actuation System With Single
Standard Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 3. Concluded

Table 4. Maximum A/B-Power Nozzle Performance of
Translating Vane Actuation System With
Three Standard Vanes Installed

[δ_p and δ_y are given in degrees]

(a) One vane deployed; two vanes retracted. $X = 1.639$ in. and $R = 0.071$ in. for 25° deployed vane

Table 4. Concluded

(b) Two vanes deployed; one vane retracted. $X = 1.639$ in. and $R = 0.071$ in. for 25° deployed vane

Table 5. Maximum A/B-Power Nozzle Performance of
Rotating Vane Actuation System With Single
Standard Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 5. Concluded

Table 6. Maximum A/B-Power Nozzle Performance of
Rotating Vane Actuation System With Two
Standard Vanes Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 7. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vane A Deployed and Vanes B and C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 7. Continued

Table 7. Concluded

Table 8. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vane A Deployed and Vanes B and C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 9. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vane B Deployed and Vanes A and C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 9. Continued

Table 9. Concluded

Table 10. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vane B Deployed and Vanes A and C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 11. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vanes A and B Equally Deployed and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 12. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vanes A and B Equally Deployed and Vane C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 13. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vanes B and C Equally Deployed and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 14. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vanes B and C Equally Deployed and Vane A Partially Retracted

[δ_p and δ_y are given in degrees]

Table 15. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vanes A and C Equally Deployed and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 16. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Three Standard Vanes Installed With Vanes A and C Equally Deployed and Vane B Partially Retracted

[δ_p and δ_y are given in degrees]

Table 17. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Single Large Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 18. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System With Large Vane and One Standard Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 19. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Deployed and Vanes B and C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 19. Continued

Table 19. Concluded

Table 20. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Deployed and Vanes B and C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 21. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Deployed and Vanes A and C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 21. Concluded

Table 22. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Deployed and Vanes A and C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 23. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Deployed and Vanes A and B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 23. Concluded

Table 24. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Deployed and Vanes A and B Partially Retracted

[δ_p and δ_y are given in degrees]

Table 25. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Equally Deployed and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 25. Concluded

Table 26. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Equally Deployed and Vane C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 27. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Equally Deployed and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 27. Concluded

Table 28. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Equally Deployed and Vane A Partially Retracted

[δ_p and δ_y are given in degrees]

Table 29. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Equally Deployed and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 29. Concluded

Table 30. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Equally Deployed and Vane B Partially Retracted

[δ_p and δ_y are given in degrees]

Table 31. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_B = 30°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

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Table 31. Concluded

Table 32. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Partially Retracted, $\delta_B = 30°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 33. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_B = 25°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 34. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Partially Retracted, $\delta_B = 25°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 35. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_B = 22.5°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 36. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_{\mathrm{B}} = 17.5°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 37. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_{\mathrm{A}} = 30°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 37. Concluded

Table 38. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Partially Retracted, $\delta_{\mathrm{A}} = 30°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 39. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_{\mathrm{A}} = 25°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 40. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Partially Retracted, $\delta_{\mathrm{A}} = 25°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 41. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_{\mathrm{A}} = 22.5°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 42. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Unequally Deployed, $\delta_{\rm A} = 17.5°$, and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 43. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_{\rm B} = 30°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 43. Concluded

Table 44. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Partially Retracted, $\delta_{\rm B} = 30°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 45. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_{\rm B} = 25°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 46. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Partially Retracted, $\delta_{\rm B} = 25°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 47. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_{\rm B} = 22.5°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 48. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_B = 17.5°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 49. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_C = 30°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 49. Concluded

Table 50. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Partially Retracted, $\delta_C = 30°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 51. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_C = 25°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 52. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Partially Retracted, $\delta_C = 25°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 53. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_C = 22.5°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 54. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Unequally Deployed, $\delta_C = 17.5°$, and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 55. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_A = 30°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 55. Concluded

Table 56. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Partially Retracted, $\delta_A = 30°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 57. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_A = 25°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 58. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Partially Retracted, $\delta_A = 25°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 59. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_A = 22.5°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 60. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_A = 17.5°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 61. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_C = 30°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 61. Concluded

Table 62. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Partially Retracted, $\delta_C = 30°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 63. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_C = 25°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 64. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Partially Retracted, $\delta_C = 25°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 65. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_C = 22.5°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 66. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Unequally Deployed, $\delta_C = 17.5°$, and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 67. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Three Vanes Equally Deployed

[δ_p and δ_y are given in degrees]

Table 67. Concluded

Table 68. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Three Vanes Partially Retracted

[δ_p and δ_y are given in degrees]

Table 69. Military-Power Nozzle Performance With No Vanes Installed

[δ_p and δ_y are given in degrees]

(a) Run 1

(b) Run 2

(c) Run 18

(d) Run 250

Table 69. Concluded

(e) Run 370

Table 70. Military-Power Nozzle Performance of Translating Vane Actuation System With Single Standard Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 70. Concluded

Table 71. Military-Power Nozzle Performance of Translating Vane Actuation System With Three Standard Vanes Installed

[δ_p and δ_y are given in degrees]

(a) One vane deployed; two vanes retracted. $X = 1.359$ in. and $R = 0.072$ in. for 25° deployed vane

Table 71. Concluded

(b) Two vanes deployed; one vane retracted. $X = 1.359$ in. and $R = 0.072$ in. for 25° deployed vane

Table 72. Military-Power Nozzle Performance of Rotating Vane Actuation System With Single Standard Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 72. Concluded

Table 73. Military-Power Nozzle Performance of Rotating Vane Actuation System With Two Standard Vanes Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 74. Military-Power Nozzle Performance of Rotating Vane Actuation System With Three Standard Vanes Installed and Deployed

[δ_p and δ_y are given in degrees]

(a) One vane deployed and two vanes retracted

Table 74. Concluded

(b) Two vanes deployed and one vane retracted

Table 75. Military-Power Nozzle Performance of Rotating Vane Actuation System With Single Large Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 76. Military-Power Nozzle Performance of Rotating Vane Actuation System With Large Vane and One Standard Vane Installed and Deployed

[δ_p and δ_y are given in degrees]

Table 77. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Deployed and Vanes B and C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 77. Concluded

Table 78. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane A Deployed and Vanes B and C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 79. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Deployed and Vanes A and C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 79. Concluded

Table 80. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane B Deployed and Vanes A and C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 81. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Deployed and Vanes A and B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 81. Concluded

Table 82. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vane C Deployed and Vanes A and B Partially Retracted

[δ_p and δ_y are given in degrees]

Table 83. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Equally Deployed and Vane C Fully Retracted

[δ_p and δ_y are given in degrees]

Table 83. Concluded

Table 84. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and B Equally Deployed and Vane C Partially Retracted

[δ_p and δ_y are given in degrees]

Table 85. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Equally Deployed and Vane A Fully Retracted

[δ_p and δ_y are given in degrees]

Table 85. Concluded

Table 86. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes B and C Equally Deployed and Vane A Partially Retracted

[δ_p and δ_y are given in degrees]

Table 87. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Equally Deployed and Vane B Fully Retracted

[δ_p and δ_y are given in degrees]

Table 87. Concluded

Table 88. Maximum A/B-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Vanes A and C Equally Deployed and Vane B Partially Retracted

[δ_p and δ_y are given in degrees]

Table 89. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Three Vanes Equally Deployed

[δ_p and δ_y are given in degrees]

Table 89. Concluded

Table 90. Military-Power Nozzle Performance of Rotating Vane Actuation System for Large Vane and Two Standard Vanes Installed With Three Vanes Partially Retracted

[δ_p and δ_y are given in degrees]

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Figure 1. Artist's concept of the F/A-18 high-alpha research vehicle (HARV) with thrust vectoring control system.

Figure 2. Sketch of single-engine propulsion simulation system with a nozzle–single-vane test configuration installed. All dimensions are given in inches.

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Figure 3. Photograph of single-engine propulsion simulation system with typical nozzle–three-vane configuration installed.

Figure 4. Sketch showing important geometry details of axisymmetric convergent test nozzle. All dimensions are given in inches unless otherwise noted.

(a) Standard vane. Vane planform area, 5.337 in^2.

Figure 5. Sketches showing geometry of thrust vectoring vanes. All dimensions are given in inches unless otherwise noted.

(b) Large vane. Vane planform area, 7.304 in^2.

Figure 5. Concluded.

(a) Nozzle and vane geometry.

Figure 6. Geometry of vane actuation systems. All dimensions are given in inches unless otherwise noted.

(b) Tables and equations defining vane center of rotation. $x = X + 5.204$; $r = H + R - 1.000$.

Figure 6. Concluded.

Figure 7. Sketches showing thrust vectoring vane positions relative to nozzle exit. Vanes are shown undeflected and with supports omitted for clarity.

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(a) Three vanes fully retracted. $\delta_A = \delta_B = \delta_C = -10^\circ$.

Figure 8. Thrust vectoring vanes installed on military-power nozzle.

(b) Two vanes deployed; one vane retracted. $\delta_A = 25^\circ$; $\delta_B = 25^\circ$; $\delta_C = -10^\circ$.

Figure 8. Concluded.

Figure 9. Baseline nozzle internal performance with vanes off.

(a) Vanes A and B deployed; vane C retracted.

Figure 10. Effect of vane actuation system on performance of maximum A/B-power nozzle with three equivalent vanes installed. Open symbols denote translating vane system; solid symbols denote rotating vane system.

(b) Vanes B and C deployed; vane A retracted.

Figure 10. Continued.

(c) Vanes A and C deployed; vane B retracted.

Figure 10. Concluded.

Figure 11. Effect of top vane size on performance of maximum A/B-power nozzle with rotating-vane actuation system. Open symbols denote standard top vane geometry; solid symbols denote large top vane geometry.

Figure 12. Effect of top vane size on performance of military-power nozzle with rotating-vane actuation system. Open symbols denote standard top vane geometry; solid symbols denote large top vane geometry.

(a) Vane A deployed.

Figure 13. Thrust and turning performance for maximum A/B-power nozzle with large top vane.

(b) Vane B deployed.

Figure 13. Continued.

(c) Vane C deployed.

Figure 13. Concluded.

(a) Vanes A and B equally deployed.

Figure 14. Thrust and turning performance for maximum A/B-power nozzle.

(b) Vanes B and C equally deployed.

Figure 14. Continued.

(c) Vanes A and C equally deployed.

Figure 14. Concluded.

(a) Vanes A and B deployed with $\delta_B = 30°$.

Figure 15. Thrust and turning performance for maximum A/B-power nozzle with two vanes deployed and one vane retracted.

(b) Vanes A and B deployed with $\delta_A = 30°$.

Figure 15. Continued.

(c) Vanes A and C deployed with $\delta_C = 30°$.

Figure 15. Continued.

(d) Vanes A and C deployed with $\delta_A = 30°$.

Figure 15. Continued.

(e) Vanes B and C deployed with $\delta_C = 30°$.

Figure 15. Continued.

(f) Vanes B and C deployed with $\delta_B = 30°$.

Figure 15. Concluded.

(a) Vane A deployed.

Figure 16. Thrust and turning performance for military-power nozzle with single vane deployed and two vanes retracted.

(b) Vane B deployed.

Figure 16. Continued.

(c) Vane C deployed.

Figure 16. Concluded.

(a) Vanes A and B equally deployed.

Figure 17. Thrust and turning performance for military-power nozzle with two equally deployed vanes with one vane retracted.

(b) Vanes B and C equally deployed.

Figure 17. Continued.

(c) Vanes A and C equally deployed.

Figure 17. Concluded.

Figure 18. Resultant thrust vectoring envelope for maximum A/B-power nozzle for maximum deflection angle of 30° with one vane always fully retracted. Operating NPR for F/A-18 HARV is approximately 4.

Figure 19. Resultant thrust vectoring envelope for military-power nozzle for maximum deflection angle of 30° with one vane always fully retracted. Operating NPR for F/A-18 HARV is approximately 4.